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Testing of PCM heat storage modules with solar collectors as heat source

Gerald Englmaier^{a*}, Mark Dannemand^a, Jakob B. Johansen^a, Weiqiang Kong^a, Janne Dragsted^a, Simon Furbo^a, Jianhua Fan^a

^aDepartment of Civil Engineering, Technical University of Denmark, Brovej 118, DK-2800 Kgs. Lyngby, Denmark

Abstract

A latent heat storage based on the phase change material Sodium Acetate Trihydrate (SAT) has been tested as part of a demonstration system. The full heat storage consisted of 4 individual modules each containing about 200 kg of sodium acetate trihydrate with different additives. The aim was to actively utilize the ability of the material to supercool to obtain long storage periods. The modules were charged with solar heat supplied by 22.4 m² evacuated tubular collectors. The investigation showed that it was possible to fully charge one module within a period of 270 minutes with clear skies. In long periods with high level of irradiance several modules were charged in parallel due to the limited heat exchange capacity of the integrated heat exchanger of the modules. After the modules were heated to more than 80° C they were set to passively cool down. Modules reached 30°C in a period of parallel cool down without the sodium acetate trihydrate solidified in 3 of the 4 modules. Further tests showed that stable supercooling at ambient temperature is possible.

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Keywords: Phase change material; PCM; Seasonal heat storage; Sodium acetate trihydrate; Compact thermal energy storage; Stable supercooling

1. Introduction

To integrate more solar energy into existing energy supply systems, long term heat storage is desired. The investigated heat storage concept is based on the principle of utilizing stable supercooling of a Phase Change Material (PCM). If Sodium Acetate Trihydrate (SAT), which has a melting point of 58 °C, has been fully melted, it

* Corresponding author. Tel.: +45 45251700;
E-mail address: gereng@byg.dtu.dk

can cool down to ambient temperature in its liquid phase without releasing the heat of fusion. Having a PCM rest in supercooled state in temperature equilibrium with the ambient allows principally seasonal heat storage in compact systems [1]. To achieve stable supercooling in heat storage modules with SAT, a minimum material temperature of 80 °C must be achieved during the heating in all parts of the material volume, according to the experimental experience. The principle is shown in Fig.1.

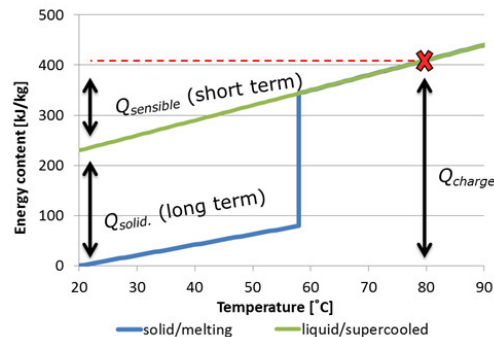


Fig. 1. Principle of stable supercooling with sodium acetate trihydrate.

The PCM heat storage can be used for short term heat storage by utilizing the sensible heat (Q_{sensible}) of the melted and supercooled PCM. The heat storage module can be left at ambient temperature with no heat loss until there is a heat demand (as long term heat storage). In that case solidification is activated, the heat of fusion (Q_{solid}) is released, and the module temperature increases almost immediately to the melting temperature.

In this paper data from initial testing of heat storage modules, containing different mixtures of the PCM sodium acetate trihydrate, are presented. Modules in different material configurations have previously been tested under laboratory conditions to prove the concept [2]. The modules form a long term heat storage as a part of a solar combi-system including additionally a solar collector field and a water buffer storage. The solar combi-system was connected to an automated tapping system simulating domestic hot water tapping and space heating demands. The overall system design and its functionality were explained by J. B. Johansen et al. [3].

2. Method

Four modules were tested with different phase change materials based on SAT. The modules were assembled to a heat storage stack and charged via a plate heat exchanger by heat from the solar collector loop.

2.1. PCM modules

A schematic drawing of the PCM module is shown in Fig.2. The modules were fabricated with an internal height of 5 cm of a closed material chamber (volume: 150 litre) by Nilan A/S. Two of the modules were in stainless steel. The other two modules were in steel. The water volume in the heat exchanger of each module was 32 litres. An air expansion volume, connected to the expansion vessel, ensured limited change of pressure during material expansion (about 10%) from solid to liquid state. A PCM temperature sensor was placed in a probe on one end of the module.

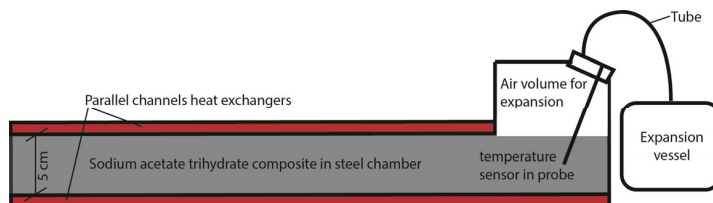


Fig. 2. Schematic module design with expansion vessel.

To overcome the problem of phase separation of the incongruently melting sodium acetate trihydrate, different PCM composites were filled into the modules. One proposed solution is to add a thickening agent to the PCM [4]. Therefore, CarboxyMethyl Cellulose (CMC) was used as thickening agent in two of the modules. One drawback of thickening agents is reduced heat transfer by convection because the thickness agents increase significantly viscosity of the PCM in its liquid phase. To counter balance this effect, a highly conductive graphite powder (C) was added in one module to increase thermal conductivity of the PCM composite.

Table 1. Configuration of the heat storage modules.

	Module 1	Module 2	Module 3	Module 4
Tank material	Carbon steel	Stainless steel	Carbon steel	Stainless steel
PCM composite	SAT + 1% CMC + 2% C + 5l Oil	SAT + 1% CMC	SAT + 1% H ₂ O + 1% EDTA	SAT + 2 % EDTA
PCM mass	202 kg	220 kg	202 kg	158 kg

Another factor that reduces heat transfer in solid SAT is insulating cavities formed during solidification and contraction of the PCM due to the density difference during phase change [5]. Adding Paraffin oil, which does not mix with SAT, was an attempt to increase heat transfer by having the oil filling in the cavities of the PCM [4].

Another possible solution for reducing the problem of phase separation is adding additives which increase the solubility of the crystal water in the melted and supercooled SAT mixture. Therefore SAT composites with Ethylenediaminetetraacetic Acid (EDTA) with and without extra water were tested. The actual PCM composites filled in modules are given in Table 1.

2.2. Heat storage

All modules were arranged separately, packed in 10 cm of foam insulation. The four modules were stacked in a 2 m high assembly (Fig.3-b). Motor valves (V1, V2, V3, or V4) were placed in front of each module, controlling flow through the module's heat exchangers (Fig.3-a). The PCM heat storage was preferably charged module by module. Both, the upper and the lower heat exchanger of a module, were active during periods of charge.

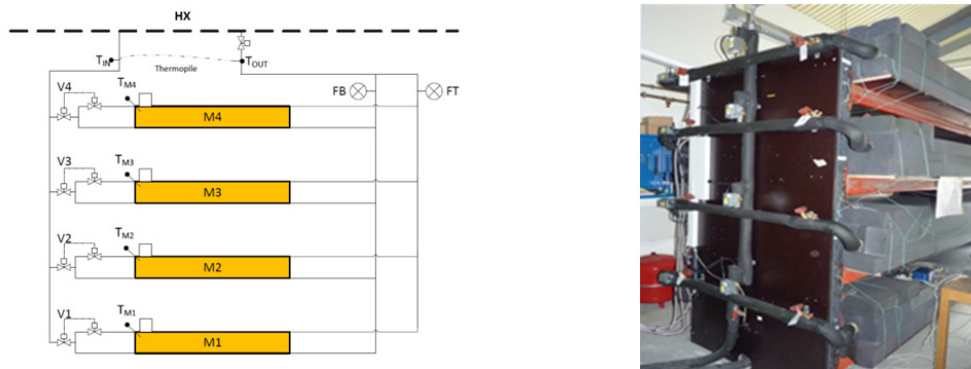


Fig. 3. (a) Hydraulic scheme of the PCM charging loop; (b) Photography of the front side of the heat storage.

In the PCM charging loop (Fig.3-a) the flow rates of the lower heat exchangers (FB) and the upper heat exchangers (FT) were measured separately. Two motor-valves per module were necessary to avoid natural circulation during cool down and unwanted backflows in inactive modules during charge. The charge of a module was stopped when it was considered to be melted i.e. the measured PCM temperature in the probe (T_{M1}, T_{M2}, T_{M3} or T_{M4}) was above 80°C. Inlet temperature (T_{IN}) and outlet temperature (T_{OUT}) were measured in the pipework to the heat exchanger (HX), where the heat was supplied from the collector loop.

Due to limited heat exchange capacity rates of the module's heat exchangers, parallel module charge was optionally enabled. This means that it was possible to charge more than one module at the same time. In this way overheating of the heat transfer fluid was prevented.

2.3. Heat transfer from the collector field

As the heat source, a solar collector field, consisting of 7 modules of Kingspan HP450 evacuated tubular collectors with a total aperture area of 22.4 m², was utilized. The field was placed on a roof with an inclination angle of 45° and an azimuth angle of 12° towards east. The system was located at the solar heating test facility of the Technical University of Denmark (northern latitude of 55.8°). As illustrated in Fig.4, the heat supplied by the collectors was transferred via a collector loop and a plate heat exchanger (HX) to the PCM charging loop (Fig.3 -a).

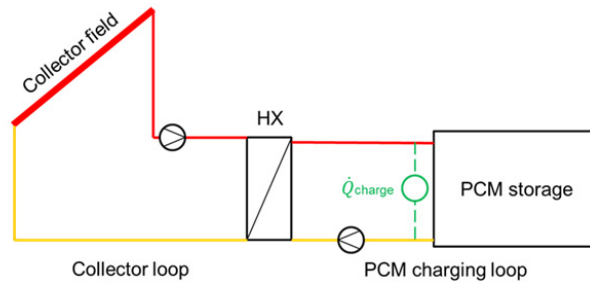


Fig. 4. Heat transfer during module charge (schematic).

The PCM modules needed to be operated with high inlet temperatures. Therefore, during PCM charge the collector loop as well as the PCM charging loop was circulated when the heat transfer fluid reached 70°C at the collector field outlet. Circulation was interrupted whenever this temperature level was undershot due to fluctuations of solar irradiance. A water volume flow rate of 16.5 l/min was realized in the PCM charging loop to ensure good heat transfer at the module's heat exchangers. The set flow rate in the collector loop was 21 l/min during PCM storage charge.

2.4. Evaluation

Charging and cool down behaviour were evaluated by measurements of the PCM temperatures in the four modules.

Heat transfer rates in the PCM charging loop were calculated in the following way:

$$\dot{Q}_{charge} = \dot{V} \cdot c_p \cdot \rho \cdot (T_{IN} - T_{OUT}) \quad (1)$$

Where \dot{V} is the measured volume flow rate of the heat transfer fluid, T_{IN} is the fluid temperature at the inlet to the modules, T_{OUT} is the fluid temperature at the outlet from the modules, c_p is the specific heat capacity of the heat transfer fluid at mean temperature between T_{IN} and T_{OUT} , ρ is the density of the heat transfer fluid at T_{OUT} , where the volume flow rates were measured.

The state of charge (SOC) of a module during single module charge was calculated based on the accumulated heat transferred to the PCM charging loop at a specific time t in relation to the total heat transferred to the module:

$$SOC(t) = \frac{\int_{start}^t \dot{Q}_{charge}}{\int_{start}^{end} \dot{Q}_{charge}} \quad (2)$$

The heat exchange capacity rate gives the power at the module's heat exchanger per Kelvin of logarithmic temperature difference between the mean heat transfer fluid temperature in the PCM charging loop and the phase change material temperature (T_{PCM}):

$$HXCR = \dot{V} \cdot c_p \cdot \rho \cdot \ln \left(\frac{T_{in} - T_{PCM}}{T_{out} - T_{PCM}} \right) \quad (3)$$

3. Results and discussion

Data from a single module charge, from a representative period of parallel module charge and from cool-down of the modules were evaluated. Supercooling was achieved by passive cool-down of modules to the ambient temperature. Although module no. 4 was frequently heated up to a probe temperature of about 85°C, no stable supercooling was achieved during the initial test period of the demonstration system.

3.1. Single module charge

In selected test runs modules have been charged individually. It was found that charging the modules in sunny afternoons matched well with the decreasing solar irradiance because the heat transfer rates during single module charge were falling with increasing PCM temperatures.

Module no. 1 was charged from ambient temperature (21°C) in solid state on the afternoon of the 8th of September. Fig.5 shows the measured solar radiation on the collector (grey curve) and the heat transferred to the modules (black, dotted curve).

Heat was transferred for 270 minutes to the heat storage, the charging (indicated by the heat transfer rate) stopped when the PCM temperature (orange curve in Fig.6) reached 80 °C. During this charge run 27.4 kWh of heat was transferred to the heat storage. The solar irradiance was fluctuating. The fluctuation of heat transfer happened with time delays. Heat transfer rates of up to 16 kW occurred at the beginning of the test. The heat transfer rates were dropping constantly until an operation time of 250 min.

In Fig.6 developments of the inlet temperature (grey curve) and the outlet temperature (black curve) are shown. As a consequence of the limited heat exchange capacity of the module, the charging loop was constantly heated up. At the end of the test, the inlet temperature dropped due to the decreasing solar irradiance (Fig.5). During the last 20 minutes the heat transfer rates were very low, since the inlet temperature, temperature of the module heat exchangers and the outlet temperature were almost the same.

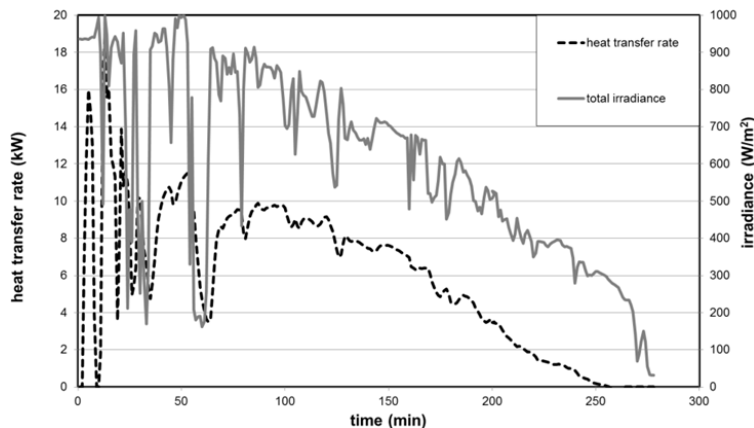


Fig. 5. Heat transfer rates during charge of module no. 1 and total irradiance development.

Until a state of charge of about 10% was reached, the heat exchange capacity rates (black dotted curve in Fig.6) were high because the heat transfer fluid in the module's heat exchangers and the pipework including the temperature sensors were heated up. Therefore a sharp increase of the outlet temperature was observed.

In between 10% and 88% of the SOC, when 78% of the heat was transferred, the HXCR was around 250 W/K.

During the last 12% of charge a sharp increase of the PCM temperature was observed. This behaviour indicated liquid PCM state at the location of the temperature probe. Because sharp increase of PCM temperature occurs when a value below 58 °C was measured and because the temperatures were even lower before 88% of charge, it is very likely that the PCM temperature does not represent the mean material temperature in the chamber. Also a PCM temperature jump at 100% charge is a proof of this assumption.

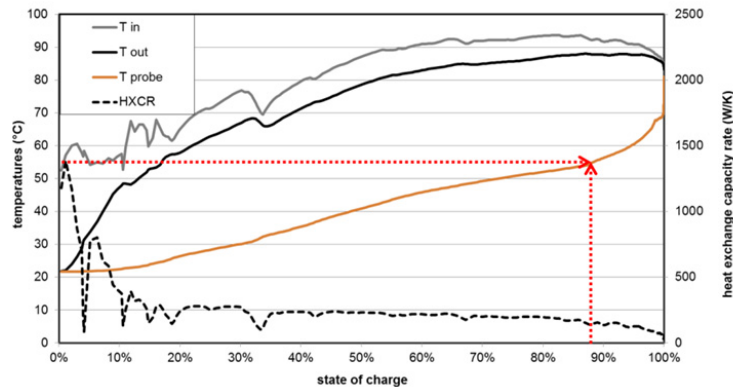


Fig. 6. Temperature developments during charge of module no. 1.

3.2. Parallel module charge

Fig.7 shows a representative period of parallel module charge in October 2015. Within two sunny days (2nd and 3rd of October), three modules were recharged by solar heat from an already supercooled state. Parallel charge at sunny days was necessary because of the limited heat exchange capacity rates of the modules. After charge, these three modules were cooled down for about five days to an equal temperature level of 30°C.

When parallel charge of modules was carried out, there were no heat transfer restrictions, due to the limited heat exchange capacity of PCM modules, occurring in the PCM charging loop. It was found that spontaneous solidification did not occur when applying heat to already supercooled modules.

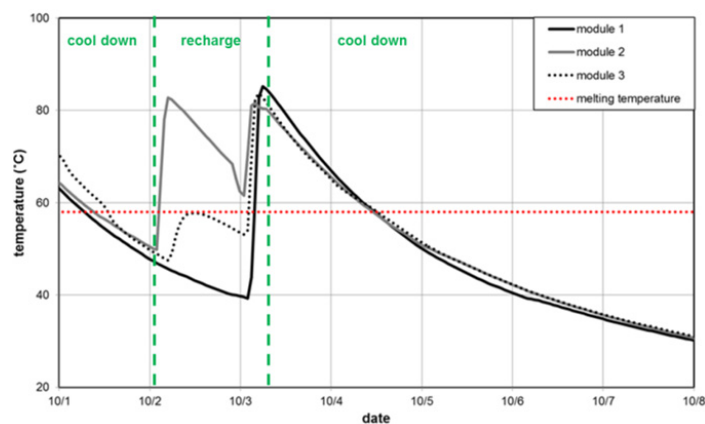


Fig. 7. PCM probe temperature developments.

3.3. Module cool-down

In two independent periods (5 days each) in August and October parallel cool down of modules showed comparable heat loss rates. Starting from a temperature of approximately 80 °C, the PCM was cooled down to a temperature of around 30 °C remaining in liquid state.

Individual module cool-down in longer periods proved that stable supercooling at ambient temperature can be achieved. In the initial test period module 2 was kept supercooled for 39 days before solidification was activated to discharge the heat of fusion [3].

The modules were installed in such a way that they could be tested individually and maintenance to each module was possible. Therefore the large surface-volume ratio of a single PCM module results in unfavourable fast cool-down. The specific heat losses of modules can be potentially, dramatically reduced by putting the flat modules together into a compact unit. In this way heat storage for short- and for long term application could be achieved.

4. Conclusions

Stable supercooling was achieved in three out of four modules after they were charged with solar collectors as a fluctuating heat source. Module no. 1, module no. 2 and module no. 3 have been successfully recharged and cooled down to 30°C in the same period. Recharge from supercooled state did not cause spontaneous solidification.

Single module charge showed that heat transfer rates allowed fast module charge from cold, solid state to melted state. Module no.1 can be charged within 270 minutes on a sunny afternoon. The development of heat transfer rates was strongly linked to the solar irradiance. During charge all pipework temperatures in the system were increasing due to the melting behavior of the PCM modules.

Because heat exchange capacity rates during charge of one module with solid PCM were only about 250 W/K, parallel module charge was necessary in long periods of sunshine. Therefore the heat storage must be designed for single and parallel module charge.

Long-term tests will show if spontaneous activation will appear during winter.

Acknowledgements

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